Epitaxial regrowth of thin amorphous GaAs layers

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Channeling and transmission electron microscopy have been used to investigate the parameters that govern the crystal quality following capless funace annealing at low temperature ($\sim$ 400 °C) in ion-implanted GaAs. From the results obtained, we concluded that the crystal quality after annealing depends strongly on the thickness of the amorphous layer generated by ion implantation and the number of residual defects increases linearly with the thickness of the implanted layer. Single-crystal regrowth free of defects detectable by megaelectron volt He^+ channeling was achieved for a very thin amorphous layer ($\lesssim$ 400 Å).

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One of the requirements of integrated circuits technology is the ability to produce thin layers of doped semiconductors with good single-crystalline structure. A well-known technique to accomplish this goal is to use ion implantation to introduce dopant impurities in single-crystalline substrates and a subsequent thermal treatment to restore the crystalline perfection of the implanted layer. While the mechanism and features of the thermal regrowth of elemental semiconductors are quite well characterized, they are currently still under investigation for compound semiconductors. For example, it has been shown only recently by Williams *et al.*[1,2] that under certain circumstances it is possible to regrow amorphous layers of ion-implanted GaAs at a temperature of 400 °C, while previously good epitaxial regrowth has been obtained only at temperatures above 600 °C.[3–5] A process for regrowing amorphous layers of GaAs generated by ion implantation at such low temperatures would constitute a real improvement in GaAs device processing because it would avoid the necessity for capping the material to prevent loss of As during the annealing. In this letter, we report measurements of regrowth at 400 °C of amorphous layers in GaAs produced by a variety of implantation conditions and the successful complete epitaxial regrowth, at this temperature, of very thin amorphous layers.

To investigate the dependence of the regrowth on the implantation conditions, semi-insulating ⟨100⟩ wafers of Cr-doped GaAs were cleaned organically and implanted with Si^+, S^+, and Ar^+ ions at energies of 80, 80, and 100 keV, respectively, to doses of 10^{14}–10^{16} atoms/cm^2. Substrate temperatures during implantation were $-$ 196 and 27 °C. In addition, As_n^+ molecules with energies of 60 ($n = 1,2,4$) and 180 ($n = 1$) keV/atom were implanted to equal atom doses at the same substrate temperatures. Samples were annealed without encapsulation at 400 °C for 60 min in flowing dry argon. They were analyzed by backscattering spectrometry of 1.5-MeV He^+ ions channeled in the ⟨100⟩ direction and detected at a scattering angle of 125 °.

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Quantitative estimates of the crystalline disorder before and after annealing were derived from the areas of the disorder peaks after applying a correction for dechanneling.

Our results showed that when the implantation produced a fully amorphous surface layer, the quality of the epitaxially regrown layer after annealing depended most strongly on the thickness of the amorphous layer generated by implantation. By comparison, the other parameters of the implantation (species, dose, substrate temperature, etc.) were found to be relatively unimportant. To show this correlation between the initial amorphous layer thickness and the residual disorder, the areas of the disorder peaks (which are proportional to the number of scattering centers per cm^2) after thermal treatment are plotted in Fig. 1 against the initial amorphous thicknesses. The thicknesses of the amorphous layer and the disorder peak areas are determined from channeling spectra recorded before and after annealing, assuming a linearly rising background beneath each disorder peak (see inset in Fig. 1). The plot in this figure clearly establishes that the number of residual defects increases linearly with the thickness of the amorphous layer produced by ion implantation. A detailed discussion of this result will be presented elsewhere.[6] It appears at once by extrapolation of this plot to "zero" residual disorder that according to this channeling analysis, very thin layers ($\lesssim$ 400 Å) of amorphous GaAs should regrow without detectable defects during annealing at 400 °C.

To check this prediction, we performed a further implantation into ⟨100⟩ GaAs with As_2^+ ions with an energy of 30 keV/atom to a dose of 10^{14} atoms/cm^2, so as to generate a very shallow amorphous layer. The substrate was held at room temperature during the implantation. We then annealed the sample at 400 °C for 60 min. Backscattering analysis was conducted at a scattering angle of 104 ° for optimum depth resolution. The spectra obtained from the as-implanted and as-annealed samples for ⟨100⟩ channeled incidence of the He^+ beam are shown in Fig. 2. The spectrum from the as-implanted sample shows a backscattering yield from a very thin surface region which is the same as that for random incidence of the beam. This fact, together with the result of an investigation of the implanted layer by transmission elec-

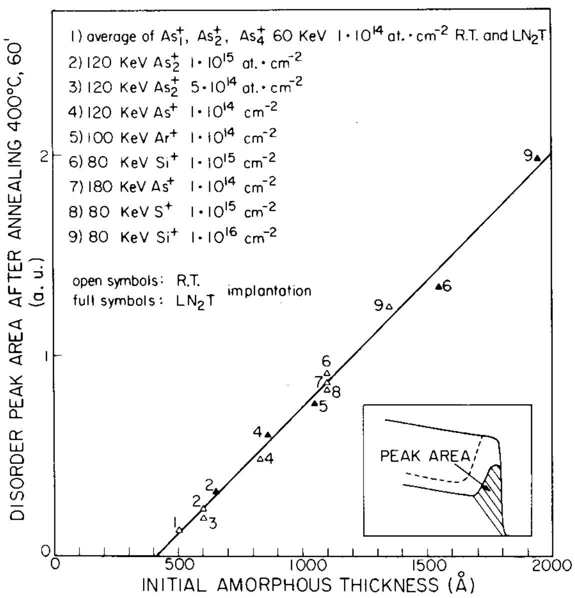

FIG. 1. Disorder peak area obtained from channeling measurements of implanted GaAs after annealing at 400 °C for 60 min plotted against the thickness of the amorphous layer generated by implantation.

tron microscopy described below indicate that the implantation produced an amorphous layer at the surface with a thickness of $\sim$400 Å.

The spectrum from the annealed samples shows a drastic reduction in the backscattering yield close to the surface, indicating good recovery of the damaged layer. A comparison with the spectrum from virgin GaAs recorded under the same experimental conditions suggests that the quality of the regrown crystal as monitored by channeling is almost as good as that of the starting material.

Microscopic information about the as-implanted layer and its crystalline structure after the 400 °C heat treatment was obtained by means of plan-view transmission electron microscopy (TEM). Figure 3 shows bright-field micrographs and transmission electron diffraction (TED) patterns from the samples of Fig. 2. The micrograph from the unannealed sample is essentially featureless [Fig. 3(a)]. The transmission electron diffraction pattern taken from a thin surface region of the sample shows diffuse rings together with single-crystal spots. The diffuse rings indicate the thin irradiated layer that had become amorphous during the implantation. The spots are generated by the underlying single-crystal substrate material that was also present in the analyzed area. The micrograph of the annealed sample showed dark spots 150–200 Å across with a density of $3\times10^9/cm^2$. No extra spots were observed in the TED pattern, indicating the absence of precipitates. However, owing to their small size, the nature of these dotlike defects remains ambiguous. No such defects were observed in micrographs taken before and after annealing on test samples that had not been implanted.

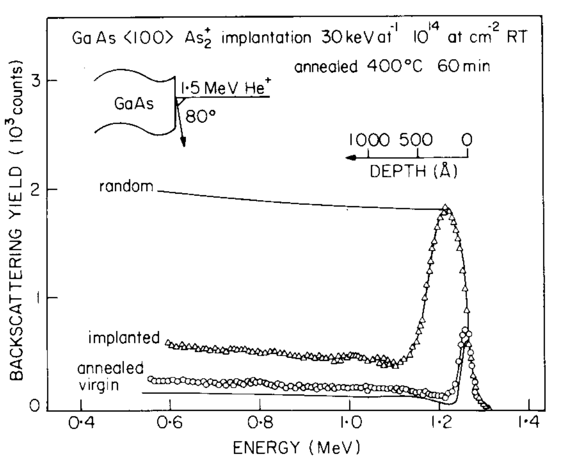

FIG. 2. High-resolution backscattering energy spectra of 1.5-MeV He^+ at random and ⟨100⟩ incidence for GaAs implanted at room temperature with 30-keV/atom As_2^+ ions to a dose of 10^{14} atoms/cm^2 and after annealing at 400 °C for 60 min.

To compare our results with those of other low-temperature annealing studies, one should note first that some of the samples in our study were irradiated to doses that substantially exceed the minimum dose for amorphization. For example, the irradiation doses of samples 6 and 9, Fig. 1 differ by a factor of 10. The resulting widths of the initial amorphous layers differ by only about 30%. The total energy deposited by the irradiation in the two amorphous layers is thus quite different. Furthermore, amorphous layers of similar widths have been generated by irradiation with ions of quite different masses (e.g., samples 6 and 7 in Fig. 1). The

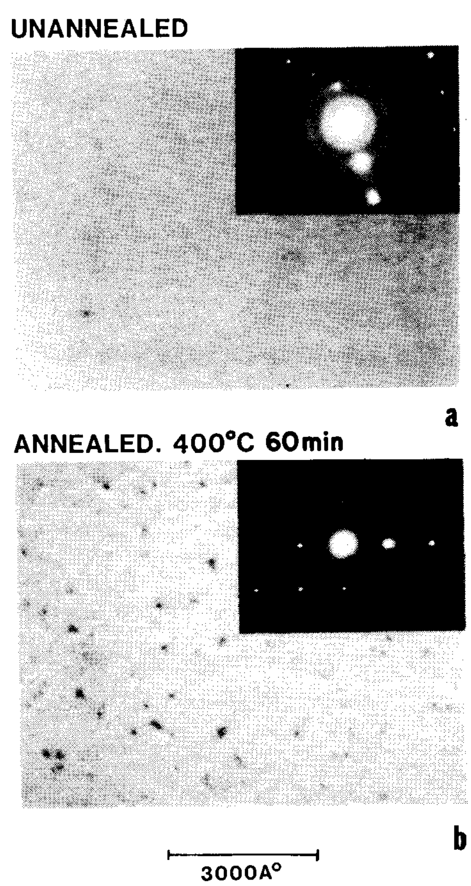

FIG. 3. TEM bright-field plan-view micrographs of the sample implanted with As_2^+ ions at 30 keV/atom to 10^{14} atoms/cm^2 at room temperature before (part a) and after (part b) annealing at 400 °C for 60 min. Diffraction patterns are inset.

amount of local disorder produced by the irradiation increases with the mass of the incident ion, so that in these cases also, the number of atomic displacements introduced in the amorphous layers differs greatly. Finally, some samples were irradiated at room temperature, where partial annealing is possible during irradiation,[7] while others were irradiated at LN_2 temperature (e.g., sample 4 in Fig. 1). In all cases, the doses of irradiation were either above, or far above, the threshold for amorphization as it is defined by channeling measurements.

The fact that a universal plot such as Fig. 1 exists thus means that these distinct ways of generating an amorphous layer are of secondary significance. As far as the thermal regrowth is concerned, there appears to be only one amorphous state. It is the thickness of that amorphized layer that determines the amount of residual disorder after annealing. In constrast, Williams and Austin have found that at the amorphization threshold, the amount of residual disorder after low-temperature annealing is a sensitive function of the irradiation conditions.[2] They report a complete regrowth of layers as thick as 1000 Å with little residual damage if an Ar^+ or S^+ irradiation at LN_2 temperature is terminated as soon as the full amorphization of the layer is accomplished. For irradiation doses in excess of this threshold, the residual damage increases and tends toward results that are similar to those reported here.

Gamo *et al.*[8] hypothesized that the incomplete regrowth of heavily amorphized layers at low temperatures is due to local variations of the stoichiometry in the implanted layer that cannot be restored during heat treatment below about 600 °C. Williams and Austin[2] suggested that the excessive disruption of stoichiometry is perhaps avoided when the irradiation is performed with Ar ions, that are lighter than the Zn and Se ions employed by Gamo *et al.*, and when the dose is just sufficient to amorphize the surface layer. According to these ideas, the total density of energy deposited by the irradiation in the amorphous layer and the atomic displacements produced by an incident ion along its track should have a major effect on the regrowth of amorphized layers at low temperatures.

The results reported in Fig. 1 refute these notions for irradiations above the threshold dose for full amorphization. One may argue that this finding is understandable on the grounds that once the stoichiometry has been locally disrupted, further irradiation will not materially alter that fact. To explain the good regrowth observed with Ar^+ irradiation at the threshold dose, it is then necessary to acknowledge that the threshold of amorphization that is measured by channeling is reached before the stoichiometry is disturbed everywhere. Although this view could be taken, the result of Fig. 2 indicates that the disruption of stoichiometry by itself is not sufficient to explain incomplete annealing. In that experiment, the amorphization was performed by a molecular beam of a heavy ion to a dose well above the threshold for amorphization. Yet the layer regrows well, because it is thin. Unless this result is peculiar to the particular irradiation conditions chosen in this experiment, one has to conclude that in general stoichiometric considerations alone do not explain the incomplete regrowth of heavily amorphized layers at low temperatures. It seems worthwhile to further strengthen or refute this conclusion by additional experiments on the regrowth of layers less then about 400 Å amorphized under various conditions of irradiation.

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